Docket No.: MP0396

APPLICATION

FOR

UNITED STATES LETTERS PATENT

TITLE: SCALABLE SPACE-FREQUENCY CODING FOR MIMO SYSTEMS

APPLICANT: HEMANTH SAMPATH and RAVI NARASIMHAN

CERTIFICATE OF MAILING BY EXPRESS MAIL

Express Mail Label No. EV 399 312 234 US

January 28, 2004
Date of Deposit

SCALABLE SPACE-FREQUENCY CODING FOR MIMO SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Application Serial No. 60/494,204, filed on August 11, 2003, which is hereby incorporated by reference in its entirety.

BACKGROUND

[0002] Wireless phones, laptops, PDAs, base stations and other systems may wirelessly transmit and receive data. A single-in-single-out (SISO) system may have two single-antenna transceivers in which one predominantly transmits and the other predominantly receives. The transceivers may use multiple data rates depending on channel quality.

[0003] An M_R X M_T multiple-in-multiple-out (MIMO) wireless system uses multiple transmit antennas (M_T) and multiple receive antennas (M_R) to improve data rates and link quality. The MIMO system may achieve high data rates by using a transmission signaling scheme called "spatial multiplexing," where a data bit stream is demultiplexed into parallel independent data streams. The independent data streams are sent on different transmit antennas to obtain an increase in data rate according to the number of

transmit antennas used. Alternatively, the MIMO system may improve link quality by using a transmission signaling scheme called "transmit diversity," where the same data stream (i.e., same signal) is sent on multiple transmit antennas after appropriate coding. The receiver receives multiple copies of the coded signal and processes the copies to obtain an estimate of the received data.

[0004] The number of independent data streams transmitted is referred to as the "multiplexing order" or spatial multiplexing rate (M). A spatial multiplexing rate of M = 1 indicates pure diversity and a spatial multiplexing rate of M = min(M_R, M_T) (minimum number of receive or transmit antennas) indicates pure multiplexing.

SUMMARY

[0005] A wireless system, e.g., a Multiple-In-Multiple-Out (MIMO)-Orthogonal Frequency Division Multiplexing (OFDM) system, may select a spatial multiplexing rate (M) from a number of available rates based on the channel conditions. The number of available mapping permutations for a given multiplexing rate may be given by

$\binom{M_T}{M} = \frac{M_T!}{M! \times (M_T - M)!}$, wherein M is the spatial multiplexing rate and M_T is the number of antennas. The available

multiplexing rates may include pure diversity, pure multiplexing, and one or more intermediate spatial multiplexing rates.

[0006] A coding module in a transmitter in the system may space frequency code OFDM symbols for transmission. The coding module may include mapping one or more data symbols, depending on the spatial multiplexing rate, to a number of antennas. The coding module may map the appropriate number of symbols to the antennas using different mapping permutations for different tones in the symbol. The mapping permutations may be applied cyclically, and may be different for adjacent tones or applied to blocks of tones.

[0007] The space frequency coding may provide substantially maximum spatial diversity for the selected spatial multiplexing rate. Also, such coding may enable transmission at a substantially equal power on each of the antennas. The space frequency coded symbol may use less than all available tone-antenna combinations.

[0008] The wireless system may comply with one of the IEEE 802.11a, IEEE 802.11g, IEEE 802.16, and IEEE 802.20 standards.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Figure 1 is a block diagram of a wireless multiple-in-multiple-out (MIMO) communication system.

[0010] Figure 2 is a block diagram of a transceiver transmit section for and space-frequency coding.

[0011] Figure 3 is a block diagram of a transceiver receive section for space-frequency decoding.

[0012] Figure 4 is a flowchart describing an antenna mapping technique for multiple spatial multiplexing rates.

[0013] Figure 5 is a flowchart describing an antenna mapping technique for multiple spatial multiplexing rates in which permutations are applied in a cyclical manner.

[0014] Figures 6A-6D are plots showing antenna mappings for different spatial multiplexing rates according to an embodiment.

[0015] Figures 7A-7D are plots showing antenna mappings for different spatial multiplexing rates according to another embodiment.

DETAILED DESCRIPTION

[0016] Figure 1 illustrates a wireless multiple-in-multiple-out (MIMO) communication system 130, which includes a first transceiver 100 with multiple transmit antennas (M_T) 104 and a second transceiver 102 with multiple

receive antennas (M_R) 106. In an embodiment, each transceiver has four antennas, forming a 4x4 MIMO system. For the description below, the first transceiver 100 is designated as a "transmitter" because the transceiver 100 predominantly transmits signals to the transceiver 102, which predominantly receives signals and is designated as a "receiver". Despite the designations, both "transmitter" 100 and "receiver" 102 may transmit and receive data, as shown by the transmit sections 101A, 101B and receive sections 103A, 103B in each transceiver.

[0017] The transmitter 100 and receiver 102 may be part of a MIMO-OFDM (Orthogonal Frequency Division Multiplexing) system. OFDM splits a data stream into multiple radiofrequency channels, which are each sent over a subcarrier frequency (also called a "tone").

[0018] The transmitter 100 and receiver 102 may be implemented in a wireless local Area Network (WLAN) that complies with the IEEE 802.11 family of specifications. It is also contemplated that such transceivers may be implemented in other types of wireless communication devices or systems, such as a mobile phone, laptop, personal digital assistant (PDA), a base station, a residence, an office, a wide area network (WAN), etc.

[0019] The number of independent data streams transmitted by the transmit antennas 104 is called the "multiplexing order" or "spatial multiplexing rate" (M). A spatial multiplexing rate of M=1 indicates pure diversity, and a spatial multiplexing rate of M = min(M_R, M_T) (minimum number of receive or transmit antennas) indicates pure multiplexing.

[0020] Each data stream may have an independent coding rate (r) and a modulation order (d). The physical (PHY) layer, or raw, data rate may be expressed as $R = r \times \log_2(d) \times M$ Bps/Hz. A transmitter's PHY layer chip may support many data rates depending on the values of M, r and d.

[0021] In an embodiment, the MIMO system 130 may use combinations of diversity and spatial multiplexing, i.e., 1 ≤ M ≤ min(M_R, M_T). For example, in the 4x4 MIMO system described above, the system may select one of the four available multiplexing rate ($M \in [1,2,3,4]$) depending on the channel conditions. The system may change the spatial multiplexing rate as channel conditions change.

[0022] In an embodiment, the MIMO system employs space-frequency coding. A space-frequency code can be used to transmit symbols for varying degrees of multiplexing and diversity orders. The OFDM tone will be denoted as "t",

$t \in [1,2,...,T]$, where T is the total number of data tones per OFDM symbol. For IEEE 802.11, the total number of tones is 64, out of which 48 tones are data tones (i.e., T=48). For each $t \in [1,2,...,T]$, the space frequency code maps M symbols into M_T transmit antennas.

[0023] Figure 2 shows one embodiment of a transceiver transmit section employing OFDM modulation and space-frequency coding. The input stream may be subject to scrambling, FEC (Forward Error Correction), interleaving, and symbol mapping to generate the symbols. Other encoding techniques may be used in lieu of those described above, as well. For each OFDM tone, t, an antenna mapping module 205 maps M symbol streams $s_1(t), s_2(t), ..., s_M(t)$ onto M_T transmit antennas.

[0024] Figure 3 shows one embodiment of a transceiver receive section for decoding space-frequency coded signals. The received signals 302 on the M_R receive antenna may be subject to AGC (Automatic Gain Control), filtering, CP (Cyclic Prefix) removal, and FFT (Fast Fourier Transform) processing to yield the received symbols across OFDM tones. The received symbols may be represented as $y_1(t), y_2(t), ..., y_M(t)$. A decoder 304 processes the received symbols using linear or non-linear space-frequency receivers to yield the

estimates $\hat{s}_1(t), \hat{s}_2(t), \ldots, \hat{s}_M(t)$. ZF (Zero Forcing), MMSE (Minimum Mean Square Error) are examples of linear space-frequency detection schemes. BLAST (Bell Laboratories Layered Space-Time) and ML (Maximum Likelihood) are examples of non-linear space-frequency detection schemes.

[0025] In an embodiment, the transmit section includes a mode selector 210 and a coding module 212 (Figure 2). The mode selector 210 determines an appropriate spatial multiplexing rate (M) for the current channel conditions. The coding module may employ a mode selection technique described in co-pending U.S. Patent Application Serial No. 10/620,024, filed on July 14, 2003 and entitled "DATA RATE ADAPTATION IN MULTIPLE-IN-MULTIPLE-OUT SYSTEMS", which is incorporated herein in its entirety. The coding module 212 constructs an appropriate space-frequency code for the selected spatial multiplexing rate.

[0026] Figure 4 is a flowchart describing an exemplary space-frequency code construction operation that may be performed by the coding module 212. The coding module 212 may receive the spatial multiplexing rate M from the mode selector 210 (block 402). The coding module 212 may then identify the permutations for the rate M (block 404).

There are a total of $\binom{M_T}{M} = \frac{M_T!}{M! \times (M_T - M)!} = P$ permutations

possible for a given spatial multiplexing rate M. The coding module 212 maps M data symbols to the M_T antennas using the different permutations $p[1,\ldots,P]$ across the T tones of the OFDM symbol (block 406). In an embodiment, the permutations are applied in a cyclical manner, as described in Figure 5. For example, if the number of possible permutations (P) for a given rate M is 4, then for tone t=1, M data symbols are mapped to the M_T antennas using permutation $p(1)$ and again for tones $t=5$, $t=9$, $t=13$, etc. (block 502). For tone $t=2$, M data symbols are mapped to the M_T antennas using permutation $p(2)$ and again for tones $t=6$, $t=10$, $t=14$, etc. When all tones are coded, the OFDM symbol may be transmitted (block 408) and then decoded at the receiver 102 (block 410).

[0027] The following example describes a space-frequency coding operation for a 4x4 MIMO OFDM system, for spatial multiplexing rates M = 4, 3, 2, 1.

[0028] As shown in Figures 6A-6D, the "X"'s represent symbols 602 (for example $S_1(1)$ and so on). The x-axis indicates tone number, and the y-axis indicates the antenna number. The vertical line 604 indicates the period of repetition pattern or mapping of symbols across tones.

[0029] In the 4x4 MIMO system, the spatial frequency multiplexing rate of M = 4 indicates pure multiplexing. The space frequency code at tone "t" is given as:

[0030] $$C(t) = \begin{bmatrix} s_1(t) \\ s_2(t) \\ s_3(t) \\ s_4(t) \end{bmatrix} \qquad (1)$$

[0031] In other words, at each tone, one independent symbol is sent on each antenna as shown in Figure 6A for M=4. Here, there is only one permutation ($\binom{4}{4} = \frac{4!}{4! \times (0)!} = 1$).

[0032] The transmitted symbol is received at the receiver 102 and decoded by the decoding module 304. The received vector at OFDM tone *t* for decoding at the receiver may be represented by the following equation:

[0033] $$y(t) = H(t)c(t) + n(t) \qquad (2)$$

[0034] where *y(t)* is an M_Rx1 receive vector, $H(t) = \left[h_1(t) \ldots h_{M_T}(t)\right]$ is the M_RxM_T channel matrix at tone "t" and $h_j(t)$ is the M_Rx1 channel vector, *c(t)* is the M_Tx1 space-frequency code vector at tone *t*, and *n(t)* is the M_Rx1 noise vector.

[0035] The channel matrix inverse at each tone, *t*, is given as:

[0036] $$G(t) = pinv[H(t)] = \begin{bmatrix} g_1(t) \\ g_2(t) \\ \cdots \\ g_{M_R}(t) \end{bmatrix} \qquad (3)$$

[0037] This space-frequency code for M = 4 may be decoded using either a linear processing scheme or a non-linear processing scheme.

[0038] For example, for a ZF (linear) receiver, the transmit symbol vector is given as:

[0039] $$\hat{C}(t) = \begin{bmatrix} \hat{s}_1(t) \\ \hat{s}_2(t) \\ \hat{s}_3(t) \\ \hat{s}_4(t) \end{bmatrix} = G(t) \cdot y(t) \qquad (4)$$

[0040] The transmit symbols are obtained by slicing the symbols $\hat{s}_1(t),\ldots,\hat{s}_4(t)$ to the nearest constellation point, i.e., $s_j(t) = Q(\hat{s}_j(t))$, where Q denotes the slicing operation. The symbol streams benefit from a diversity order $D = (M_R - M_T + 1)$.

[0041] Other linear receivers include the MMSE receiver, which also incorporates the noise variance in the formulation.

[0042] For a BLAST (non-linear) receiver, the receiver first decodes the symbol $s_k(t) = Q(\hat{s}_k(t))$, where $\hat{s}_k(t)$ is obtained from equation (4) and $k = \arg\max\left(\|g_i(t)\|^2\right), i \in [1,2,3,4]$. The

contribution from the decoded symbol $\hat{s}_k(t)$ is then removed from the received vector *y(t)* to get a new system equation: $y'(t) = H'(t) + n'(t)$, where $H'(t) \leftarrow H(t)\langle_k$ and $y'(t) \leftarrow Y(t) - h_k(t)s_k(t)$. The decoding process is repeated until all symbols are decoded. The symbol decoded at the n^{th} stage benefits from a diversity order of $D = (M_R - M_T + n)$.

[0043] Other non-linear receivers include the ML receiver. However, the implementation complexity may be high compared to the linear and BLAST receivers described above.

[0044] For a spatial multiplexing rate M = 3, 3 symbols are mapped onto M_T = 4 antennas at each OFDM tone, *t*. There are a total of $\binom{4}{3} = \frac{4!}{3! \times (1)!} = 4$ permutations possible. The mappings may be chosen in an cyclical fashion as follows, as shown in Figure 6B for M=3:

[0045] For tone 1 (t=1): $C(1) = \begin{pmatrix} s_1(1) \\ s_2(1) \\ s_3(1) \\ 0 \end{pmatrix}$

[0046] For tone 2 (t=2): $C(2) = \begin{pmatrix} 0 \\ s_2(2) \\ s_3(2) \\ s_4(2) \end{pmatrix}$

[0047] For tone 3 or t=3: $C(3)=\begin{pmatrix} s_1(3) \\ 0 \\ s_3(3) \\ s_4(3) \end{pmatrix}$

[0048] For tone 4 or t=4: $C(4)=\begin{pmatrix} s_1(4) \\ s_2(4) \\ 0 \\ s_4(4) \end{pmatrix}$

[0049] and so on for higher tone numbers, in a cyclical fashion.

[0050] The receiver implementations are similar to that given above for the M = 4 case. The only difference is that the M_Rx1 column vector, $h_j(t)$, is set to zero. The column "j" corresponds to the antenna on which no symbol is transmitted (for the given tone).

[0051] For a spatial multiplexing rate M = 2, 2 symbols are mapped onto M_T = 4 antennas at each OFDM tone, t. There are a total of $\begin{pmatrix} 4 \\ 2 \end{pmatrix}=\frac{4!}{2!\times(2)!}=6$ permutations possible. The mappings may be chosen in an cyclical fashion as follows, as shown in Figure 6C for M=2:

[0052] For tone 1 (t=1): $C(1)=\begin{pmatrix} s_1(1) \\ s_2(1) \\ 0 \\ 0 \end{pmatrix}$

[0053] For tone 2 (t=2): $C(2)=\begin{pmatrix} 0 \\ 0 \\ s_3(2) \\ s_4(2) \end{pmatrix}$

[0054] For tone 3 (t=3): $C(3)=\begin{pmatrix} s_1(3) \\ 0 \\ s_3(3) \\ 0 \end{pmatrix}$

[0055] For tone 4 (t=4): $C(4)=\begin{pmatrix} 0 \\ s_2(4) \\ 0 \\ s_4(4) \end{pmatrix}$

[0056] For tone 5 (t=5): $C(5)=\begin{pmatrix} s_1(5) \\ 0 \\ 0 \\ s_4(5) \end{pmatrix}$

[0057] For tone 6 (t=6): $C(6)=\begin{pmatrix} 0 \\ s_2(6) \\ s_3(6) \\ 0 \end{pmatrix}$

[0058] and so on for higher tone numbers, in a cyclical fashion.

[0059] The receiver implementations are similar to that given above for the M = 4 case. The only difference is that the 2 M_Rx1 column vectors, $h_j(t)$ and $h_{k \neq k}(t)$, are set to zero. The columns "j" and "k" correspond to the antennas on which no symbol is transmitted (for the given tone).

[0060] For a spatial multiplexing rate M = 1, 1 symbol is mapped onto M_T = 4 antennas at each OFDM tone, t, as shown in Figure 6D for M=1. In the 4x4 MIMO system, a spatial multiplexing rate M = 1 indicates pure diversity. There are a total of $\begin{pmatrix}4\\1\end{pmatrix}=\frac{4!}{1!\times(3)!}=4$ permutations possible. The mappings may be chosen in an cyclical fashion as follows:

[0061] For tone 1 (t=1): $C(1)=\begin{pmatrix}s_1(1)\\0\\0\\0\end{pmatrix}$

[0062] For tone 2 (t=2): $C(2)=\begin{pmatrix}0\\s_2(2)\\0\\0\end{pmatrix}$

[0063] For tone 3 (t=3): $C(3)=\begin{pmatrix}0\\0\\s_3(3)\\0\end{pmatrix}$

[0064] For tone 4 (t=4): $C(4)=\begin{pmatrix}0\\0\\0\\s_4(4)\end{pmatrix}$

[0065] and so on for higher tone numbers, in a cyclical fashion.

[0066] One receiver implementation is the well-known linear-MRC receiver, which is also the ML receiver. This is given as:

[0067] $$\hat{s}_k(t) = \frac{h_k^*(t)}{\left\|h_k^*(t)\right\|^2} y(t)$$

[0068] where the column "k" corresponds to the antenna on which the symbol is transmitted on a given tone.

[0069] An advantage of the space-frequency coding (or mapping) scheme described above is that it converts the available spatially selective channel to a frequency selective channel. The outer-convolutional code (and interleaving) can hence achieve superior performance due to increased frequency selectivity. Also, not all tones are used for each transmit antenna.

[0070] Another possible advantage of the space-frequency coding technique is that the permutations ensure that equal or similar power is transmitted on all antennas regardless of the spatial multiplexing rate (M). This may make the power amplifier design requirement less stringent compared to coding techniques that transmit different power on different antennas. In other words, this scheme requires a power amplifier with lower peak power, which may provide cost savings. The space frequency coding technique also ensures that all transmit antennas are used regardless of

the spatial multiplexing rate. Consequently, maximum spatial diversity is captured at all times. This condition also facilitates the receiver automatic gain control (AGC) implementation, since the power is held constant across the whole length of the packet. This is in contrast to systems with antenna selection, in which case some antennas may not be selected as a result of which the receiver power can fluctuate from symbol to symbol, complicating AGC design.

[0071] Another advantage of the space-frequency coding technique is that such a system can incorporate MIMO technology into legacy systems (e.g., IEEE 802.11a/g systems), while maintaining full-backward compatibility with legacy receivers in the rate 1 mode (M=1, or pure diversity). In this mode, with each transmitter transmitting 1/M of the total power, the legacy receivers cannot tell that the data is indeed being transmitted from multiple transmit antennas. Hence, no additional overhead is required to support legacy systems. The rate M=1 can be used in legacy (11a,11g) systems.

[0072] Another advantage is that the above space-frequency coding scheme does not use all tone-antenna combinations. This lowers the amount of training required since channels corresponding to only a subset of tone-

antenna combinations need to be trained. This may improve throughput by simplifying preamble design.

[0073] One of the main problems in OFDM systems is Inter-carrier interference (ICI) due to phase noise, and frequency offset It is well known that the ICI effects are more severe in frequency selective channels. In an embodiment, a new permutation is chosen after several tones instead of after each tone, as shown in Figures 7A-7D. This reduces the number of "hops" across the tones, which in turn reduces frequency selectivity and hence ICI, leading to improved performance.

[0074] In the embodiments described above, the permutations can be viewed as multiplying the symbols transmitted on each antenna for a given tone by unity or zero. For the M=2 case given above, the permutation for tone 1 is given by:

[0075] $$C(1)=\begin{pmatrix} s_1(1) \\ s_2(1) \\ s_3(1) \\ s_4(1) \end{pmatrix} \times \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} s_1(1) \\ s_2(1) \\ 0 \\ 0 \end{pmatrix}.$$

[0076] However, in alternative embodiments, the symbols may be multiplied by other (possibly complex) scalars to produce the permutations.

[0077] The space-frequency coding techniques described may be implemented in many different wireless systems, e.g.,

systems compliant with IEEE standards 802.11a, 802.11g, 802.16, and 802.20.

[0078] A number of embodiments have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. For example, blocks in the flowcharts may be skipped or performed out of order and still produce desirable results. Accordingly, other embodiments are within the scope of the following claims.